Project title: ENHANCEMENT AND DEVELOPMENT OF NUMERICAL MODELS FOR SIMULATING COASTAL SEDIMENT TRANSPORT AND MORPHOLOGY EVOLUTION

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ENHANCEMENT AND DEVELOPMENT OF NUMERICAL MODELS FOR SIMULATING COASTAL SEDIMENT TRANSPORT AND MORPHOLOGY EVOLUTION

I. SCIENTIFIC WORK ACCOMPLISHED

Task 01-03: Lund-CIRP Sediment Transport Model

Background

Accurate prediction of sediment transport rates is an important element in morphological studies for the coastal environment. Most of the existing formulas used in numerical models compute current-related sediment transport only. This component of the sediment transport generally prevails in the longshore direction. However, in the cross-shore direction the waves do not only increase the quantity of sediment available for transport, but they also strongly affect the direction of the sediment transport (Dibajnia and Watanabe 1992 Ribberink and Al Salem 1994). First, asymmetric waves induce onshore wave-related sediment transport. Second, phase-lag in the sediment suspension (which occurs in case of ripples or sheet flow) may reduce the total net sediment transport and even induce a net transport opposite to the wave direction. Ribberink and Al Salem (1994) showed that, assuming the velocity ($u(z)$) and concentration ($c(z)$) equal to a constant part ($\overline{u}(z)$ and $\overline{c}(z)$) and a fluctuating part ($\tilde{u}(z)$ and $\tilde{c}(z)$), the net sediment transport rate ($q_{s,net}$) may be written as the sum of a current-related sediment transport and a wave-related sediment transport according to,

$$q_{s,net} = \int_0^h \overline{u}(z)\overline{c}(z)dz + \int_0^h \tilde{u}(z)\tilde{c}(z)dz \qquad (1)$$

where h is the water depth and z a vertical coordinate. Both components of the sediment transport may be significant in the nearshore zone. Camenen and Larson (2005a, b; 2006a, b; 2007) proposed a bed load and suspended load formula for the nearshore calibrated with a large amount of data from both laboratory and field measurements addressing the components contained in Eq. 1.

Objectives

The main objectives of this task were: (1) to further develop and validate the sediment transport formulas by Camenen and Larson (2005a, 2006a, 2007) collectively denoted as the Lund-CIRP model; and (2) to present the Lund-CIRP model in a comprehensive technical report.

Procedure and Results

No modifications were made to the previously developed bed load sediment transport formula (Camenen and Larson 2005a), but the suspended load formula was modified with respect to the calculation of the vertical sediment diffusivity. The sediment

diffusivity is related to the total energy dissipation in which the energy dissipation from wave breaking (D_b) and from bottom friction due to current (D_c) and waves (D_w) are added,

$$\varepsilon = \left(\frac{k_c{}^3 D_c + k_w{}^3 D_w + k_b{}^3 D_b}{\rho} \right)^{1/3} h \tag{2}$$

where k_b, k_c and k_w are coefficients with $k_b = 0.01$ corresponding to an efficiency coefficient related to dissipation due to wave breaking, whereas k_c and k_w are associated with the Schmidt number. Assuming the Rouse parabolic profile to be a correct approximation of the vertical sediment diffusivity, for a steady current or non-breaking waves its mean value over the depth may be written,

$$\varepsilon_{c/w} = k_{c/w} \left(\frac{D_{c/w}}{\rho} \right)^{1/3} h = \frac{C_w \sigma_{c/w}}{6} \kappa u_{*c/w} h \tag{3}$$

where $\sigma_{c/w}$ is the Schmidt number or the ratio between the vertical eddy diffusivity of the particles ε_v and the vertical eddy viscosity ν_v and $u_{*,c/w}$ is the shear velocity due to current or waves only, respectively, κ von Karman's constant, and $C_w = 1$ in case of current or $C_w = 2/\pi$ in case of waves (this coefficient results from a time-average assuming a sinusoidal wave). Based on the analysis of a wide range of experimental data, the following expressions were developed for the Schmidt numbers $\sigma_{c/w}$:

$$\sigma_{c/w} = \begin{cases} A_1 + A_2 \sin^2\left(\dfrac{\pi}{2} \dfrac{W_s}{u_{*,cw}} \right) & if \quad \dfrac{W_s}{u_{*,cw}} \leq 1 \\ 1 + \left(A_1 + A_2 - 1 \right) \sin^2\left(\dfrac{\pi}{2} \dfrac{u_{*,cw}}{W_s} \right) & if \quad \dfrac{W_s}{u_{*,cw}} > 1 \end{cases} \tag{4}$$

where $A_1 = 0.4$ and $A_2 = 3.5$ in case of a steady current only, and $A_1 = 0.15$ and $A_2 = 1.5$ in case of waves only. For wave-current interaction, a weighted value is used for the Schmidt number, $\sigma_{cw} = X_t \sigma_c + (1 - X_t) \sigma_w$ with $X_t = \theta_c / \left(\theta_c + \theta_w \right)$ and θ_c being the current Shields parameter and θ_w the wave Shields parameter.

The technical report describing the theoretical background of the Lund-CIRP model and its validation with laboratory and field data has been completed. A final draft is available and has been transferred to Dr. Nicholas C. Kraus at the Coastal and Hydraulics Laboratory in Vicksburg, MS. A copy of the table of contents is enclosed in Appendix A of this Interim Report. The entire report is available in electronic form on request.

Task 01-04: Cascade Subaerial Sediment Exchange

Background

Sediment exchange between the subaerial and sub-aqueous portion of the beach occurs primarily across-shore, driven by wave motion in the swash zone. Water level is a leading factor in this process because it defines the starting point of the swash zone and to what elevation the uprushing waves may reach. Over longer time periods, wind-blown sand may also be an important factor for the cross-shore sediment exchange on the subaerial portion of the beach. This exchange takes place between the dune and the broad, flat berm often present on the seaward side of the dune. Since Cascade simulates coastal evolution over decades to centuries, it is important to include wind-blown sand in models of cross-shore sediment exchange.

Depending on the morphology of the subaerial beach, different types of response to transport by incident waves and wind-blown sand are expected, implying supply or depletion of sediment from the sub-aqueous beach with associated advance or recession of the shoreline, respectively. Erosion of dunes or soft cliffs supplies the beach with sediment, whereas transport by wind moves sediment from the berm to the dune. Also, during severe storms, the dunes might overwash, causing transport of sediment onshore over the dune crest and deposition on the landward side of the dune crest (Donnelly et al. 2006). Thus, a physics-based approach to model the sediment exchange between the subaerial and sub-aqueous portion of the beach requires description of dunes subject to erosion by wave impact and overwash, as well as to build-up by wind-blown sand.

Objectives

The main objectives of this task were: (1) to improve the modeling of the cross-shore exchange for the subaerial portion of the beach, including the contribution of wind-blown sand; and (2) to couple the subaerial response to the evolution of the sub-aqueous portion of the beach.

Procedure and Results

Analytical models were developed of dunes built up by wind-transported sand originating from the berm/foreshore complex. Figure 1 provides a simple definition sketch of the prevailing situation together with some notation. The terminology berm is used for the near-horizontal portion of the subaerial beach close to the dune, whereas the portion of the beach regularly exposed to waves in the swash zone is denoted as the foreshore. Sand transported alongshore trapped by structures (e.g., groins), in combination with onshore transport of sand by waves, promotes an expansion of the berm that makes sand available for the dune growth. In addition, large waves during storms may attack the dune, causing erosion and retreat, supplying the beach with material that is typically deposited under water. In the following different approaches to model cross-shore sediment exchange on the subaerial portion of the beach to be used in Cascade is presented, including models that describe the interaction with the sub-aqueous portion of the beach.

Model of Dune Build-up by Wind

It is assumed that the dune is built-up by wind-transported sand taken from the berm, which in turn is supplied by material from the underwater profile conveyed through the foreshore. A simple sand conservation equation gives,

$$\frac{dV_D}{dt} = q_w \tag{5}$$

where V_D is the dune volume, t time, and q_w the sand transport from wind. If the dune height above the berm elevation (D) remains constant together with the shape, the seaward translation of the dune foot (Δx_D) for a given increase in dune volume (ΔV_D) is determined by:

$$\Delta x_D = \frac{\Delta V_D}{D} \tag{6}$$

Thus, writing Eq. 5 in terms of dune foot advance instead of volume growth yields:

$$\frac{dx_D}{dt} = \frac{q_w}{D} \tag{7}$$

In order to proceed, an expression that relates q_w to the properties of the berm/foreshore is needed. It is reasonable to assume that the sand transport to the dune is related to the width of the berm up to some distance when equilibrium conditions have developed between the wind and the sand bed. A simple equation that exhibits these properties, simultaneously as it gives a continuous description of the transport in space, is,

$$q_w = q_{wo}\left(1 - \exp\left(-\alpha\left(x_B - x_D\right)\right)\right) \tag{8}$$

where q_{wo} is the transport by wind at equilibrium (dependent on fluid and sediment properties), α a rate coefficient quantifying the approach to equilibrium, and x_B and x_D is the distance to the seaward end of the berm and the dune foot, respectively (see Figure 1; the x-axis points offshore). Another possibility would be to employ the following equation,

$$q_w = q_{wo}\tanh\left(\alpha\left(x_B - x_D\right)\right) \tag{9}$$

although this equation is more difficult to treat analytically (in a numerical implementation it makes no difference whether Eqs. 8 or 9 is employed).

Substituting in Eq. 8 into Eq. 7 gives:

$$\frac{dx_D}{dt} = \frac{q_{wo}}{D}\left(1 - \exp\left(-\alpha\left(x_B - x_D\right)\right)\right) \tag{10}$$

Assuming that x_B and q_{wo} are constants, this equation may be solved analytically. In deriving the solution it is convenient to introduce the following non-dimensional variable:

$$\xi = \exp\left(-\alpha\left(x_B - x_D\right)\right) \tag{11}$$

The solution to Eq. 10 may be written,

$$\xi = \frac{\xi_o}{\left(1-\xi_o\right)\exp\left(-\alpha q_{wo} t / D\right) + \xi_o} \tag{12}$$

where,

$$\xi_o = \exp\left(-\alpha\left(x_B - x_{Do}\right)\right) \tag{13}$$

and subscript *o* denotes conditions at t=0. Equation 12 can be expressed in dimensional form as:

$$x_D = x_B + \frac{1}{\alpha}\ln\left(\frac{\xi_o}{\left(1-\xi_o\right)\exp\left(-\alpha q_{wo} t / D\right) + \xi_o}\right) \tag{14}$$

If $t \to \infty$, $x_D \to x_B$, that is, the dune foot approaches the shoreward limit of the foreshore at which time the transport rate decreases to zero. Figure 2 plots Eq. 14 in non-dimensional form where the berm width at a specific time is normalized with the initial berm width ($x' = (x_B - x_D)/(x_B - x_{Do})$; $t' = q_{wo} t/(x_B - x_{Do})D$; $\alpha' = \alpha(x_B - x_{Do})$).

Model of Dune Build-up by Wind including Erosion by Wave Impact

As discussed above, during storms when the water level is high and the wave action strong, waves may impact the dune and erode it. This material is typically transported seawards and deposited under water. Assuming that the erosion of the dune due to wave impact is q_o, Eq. 5 may be modified to:

$$\frac{dV_D}{dt} = q_w - q_o \tag{15}$$

Thus, if $q_w > q_o$ the dune will advance, $q_w < q_o$ it will retreat, and $q_w = q_o$ equilibrium prevails.

The resulting equation to solve, with the same main assumption as above is:

$$\frac{dx_D}{dt} = \frac{q_{wo}}{D}\left(1-\exp\left(-\alpha\left(x_B - x_D\right)\right)\right) - \frac{q_o}{D} \tag{16}$$

For simplicity q_o is taken to be a constant representing an average loss of material from the dune due to wave impact. Introducing the following non-dimensional variable,

$$A = \frac{q_{wo} - q_o}{q_{wo}} \tag{17}$$

the solution to Eq. 16 may be written:

$$\xi = \frac{A\xi_o}{\left(A-\xi_o\right)\exp\left(-\alpha A q_{wo} t / D\right) + \xi_o} \tag{18}$$

If q_o=0, A=1 and Eq. 18 reverts back to Eq. 12. If $t \to \infty$, $\xi \to A$ for $A > 0$, whereas for $A < 0$ there is no asymptotic solution, but erosion continues indefinitely. Thus, if the potential transport by wind is larger than the erosion due to wave impact ($q_{wo} > q_o$, that is, $A > 0$), the equilibrium width (l_e) is obtained as,

$$l_e = \left(x_B - x_D\right)_\infty = \frac{1}{\alpha}\ln\left(\frac{q_{wo}}{q_{wo} - q_o}\right) \tag{19}$$

where subscript e denotes equilibrium conditions. This expression can also be obtained by setting $q_w = q_o$ in Eq. 8. Figure 3 plots Eq. 19 in non-dimensional form with $l_e' = l_e/(x_B - x_{Do})$; $q_o' = q_o/q_{wo}$; $\alpha' = \alpha(x_B - x_{Do})$.

Model of Dune Build-up by Wind Including Shoreline Change

In the solution given by Eq. 12, the seaward end of the berm was fixed, assuming that material supplied to build the dune was provided from the underwater portion of the profile without any profile retreat. A more realistic approach would be to let the profile retreat to build the dune. Thus, if a volume of ΔV_D is added to the dune, the same volume should be taken from the profile over its active depth, which includes the vertical distance from the berm crest (D_B) to the depth of closure (D_C). Under the assumption that dune and beach profile change occur with preserved shape, continuity requires that:

$$\Delta x_D D = \Delta x_B\left(D_B + D_C\right) \tag{20}$$

Equation 20 may be re-arranged to yield:

$$\Delta x_B = \Delta x_D \frac{D}{D_B + D_C} \tag{21}$$

This equation provides a simple estimate of the needed profile retreat to produce a certain dune advance.

The retreat of the profile implies a shoreward translation of x_B that will reduced the width of the berm and the magnitude of the sand transport by wind to the dunes. The equations governing the movement of the dune foot and the berm crest, respectively, are:

$$\frac{dx_D}{dt} = \frac{q_{wo}}{D}\left(1 - \exp\left(-\alpha\left(x_B - x_D\right)\right)\right) \tag{22}$$

$$\frac{dx_B}{dt} = -\frac{q_{wo}}{D_B + D_C}\left(1 - \exp\left(-\alpha\left(x_B - x_D\right)\right)\right) \tag{23}$$

Combining these two equations yield:

$$\frac{d}{dt}\left(x_B - x_D\right) = -\frac{q_{wo}}{D}\left(1 + \frac{D}{D_B + D_C}\right)\left(1 - \exp\left(-\alpha\left(x_B - x_D\right)\right)\right) \tag{24}$$

If $D_B + D_C \rightarrow \infty$, Eq. 24 reverts back to Eq. 10 (note that $dx_B/dt=0$), which means no effect on the beach profile from the dune build-up.

Introducing $w = x_B - x_D$, Eq. 24 becomes,

$$\frac{dw}{dt} = -B\frac{q_{wo}}{D}\left(1 - \exp\left(-\alpha w\right)\right) \tag{25}$$

where:

$$B = 1 + \frac{D}{D_B + D_C} \tag{26}$$

Solving Eq. 25 gives:

$$\xi = \frac{\xi_o}{\left(1 - \xi_o\right)\exp\left(-\alpha B q_{wo} t / D\right) + \xi_o} \tag{27}$$

If $t \rightarrow \infty$, $\xi \rightarrow 1$, that is, the berm width is zero (w=0), which is the equilibrium solution for the case with no dune erosion due to wave impact. The approach to equilibrium for Eq. 27 is faster than for Eq. 12, since $B > 1$.

The movement of x_D or x_B has to be determined by substituting in Eq, 27 into Eq. 22 and 23, respectively, although it might be difficult to obtain an analytical solution (to be looked at later).

The volume conservation requirements leading to Eqs. 20 and 21 should be valid at equilibrium as well. At t=0 the berm width is $l_o = x_{Bo} - x_{Do}$ and the changes in the dune and berm location taken place to reach equilibrium must correspond to this value:

$$l_o = \Delta x_{De} + \Delta x_{Be} \tag{28}$$

Using Eq. 21 in Eq. 28 to eliminate Δx_{Be} and solving for Δx_{De} yields:

$$\Delta x_{De} = \frac{l_o}{1 + \dfrac{D}{D_B + D_C}} \tag{29}$$

The corresponding expression for the movement of the berm crest from its initial position to its equilibrium position is:

$$\Delta x_{De} = \frac{l_o}{1 + \dfrac{D_B + D_C}{D}} \tag{30}$$

Model of Dune Build-up by Wind Including Shoreline Change and Erosion by Dune Impact

In the most complete description erosion due to wave impact is included at the same time as the profile is allowed to retreat to balance the advance of the dunes. Equations 22 and 23 are modified to include the erosion due to wave impact yielding:

$$\frac{dx_D}{dt} = \frac{q_{wo}}{D}\left(1 - \exp\left(-\alpha\left(x_B - x_D\right)\right)\right) - \frac{q_o}{D} \tag{31}$$

$$\frac{dx_B}{dt} = -\frac{q_{wo}}{D_B + D_C}\left(1 - \exp\left(-\alpha\left(x_B - x_D\right)\right)\right) + \frac{q_o}{D_B + D_C} \tag{32}$$

Combining Eqs. 31 and 32, and introducing $w = x_B - x_D$ produces the following equation to solve (compare Eq. 25),

$$\frac{dw}{dt} = -\frac{q_{wo}}{D} B\left(A - \exp\left(-\alpha w\right)\right) \tag{33}$$

where A and B is defined as before.

The solution to Eq. 33 is:

$$\xi = \frac{A\xi_o}{\left(A-\xi_o\right)\exp\left(-\alpha ABq_{wo}t/D\right)+\xi_o} \tag{34}$$

The asymptotic solution to Eq. 34 for $t \to \infty$ is $\xi \to A$ (for A > 0), giving the same equilibrium berm width as given by Eq. 19. However, as for Eq. 27 the approach to equilibrium is faster when the profile is allowed to retreat.

The movement of the dune foot from its initial position to its equilibrium position has to be corrected for the equilibrium width, which is not zero as was the case for Eq. 29:

$$\Delta x_{De} = \frac{l_o - l_e}{1+\dfrac{D}{D_B+D_C}} \tag{35}$$

Equation 30 should be modified in a similar manner.

In order display the properties of Eq. 34, it is developed and written in non-dimensional form,

$$w' = \frac{1}{\alpha'}\ln\left(\frac{1}{A}\left(1-\left(1-A\exp(\alpha')\right)\exp\left(-\alpha' ABt'\right)\right)\right) \tag{36}$$

where $w' = w/w_o = (x_B - x_D)/(x_B - x_{Do})$, $t' = q_{wo}t/w_oD$, and $\alpha' = \alpha w_o$.

Figure 4 illustrates the time evolution of the berm width for various values on the ratio q_o/q_{wo} (α'=1.0 and B=4/3, which implies that the dune height D is 1/3 of D_B+D_C). As can be seen from the figure the initial berm width is lower than the equilibrium value for the smallest q_o/q_{wo}-ratio, which causes the berm width to increase.

Figure 5 displays how the berm width evolves for various values on B ($B = 1 + D/(D_B + D_C)$), where α'=1.0 and A=0.6 (corresponding to q_o/q_{wo}=0.4). As previously pointed out the effect of a relatively larger active profile height with respect to the dune height is a slower response towards equilibrium, although the effect is not very significant.

Task 01-05: Cascade Dune Impact and Overwash Modeling

Background

During severe storms high waves and water levels may greatly impact the subaerial portion of the beach inducing significant morphological change at elevations where the

waves can not reach under normal conditions. Coastal dunes may suffer direct wave impact and erode, increasing the likelihood of breaching and subsequent flooding of low-lying areas behind the dunes. Overwash occurs if the wave runup and/or the mean water level are sufficiently high allowing for water and sediment to pass the beach crest, which in turn causes flooding and deposition of sediment shoreward of the crest (Donnelly *et al.* 2006). In the case of overwash, severe lowering of the crest may take place, increasing the probability of flooding and breaching as the natural defence offered by the subaerial morphological features (e.g., dunes) is weakened.

A barrier island is another type of morphological feature that is vulnerable to high waves and water levels. Typically, these features are regularly exposed to overwash because the crest tends to be at a low elevation. The shoreward transport of sediment in connection with overwash is an important element in the sediment budget for a barrier island and this transport is also thought by many researchers to be the cause of the onshore migration that many such islands are experiencing (Fisher and Stauble 1977, Leatherman 1979). Because the crest of a barrier island is typically low-lying, the mean water level during a storm might exceed the crest elevation leading to inundation overwash. The case when the mean water level is below the crest but the runup passes over it is often denoted as runup overwash. Other morphological features such as spits, or shore-attached shoals that perch the water surface, may exhibit frequent overwash and display similarities to barrier islands in terms of the response, albeit at a smaller scale.

Objectives

The main objectives of this task were: (1) to develop a model of erosion due to wave impact and sediment transport in the overwash for use in Cascade; (2) to validate the model with high-quality field data; and (3) to develop methods to employ the model for estimating the statistical properties of morphological response in connection with storms based on long time series of input data on waves and water level.

Procedure and Results

The transport formula developed by Larson *et al.* (2004) was employed to compute dune or barrier island erosion due to wave impact. The eroded sediment is transported offshore or over the beach crest (overwash) depending on the wave and water level conditions in relation to the crest elevation. A simple analytical model was derived for a triangular subaerial cross section, which is often a good characterization of dunes and barrier islands. The model includes three variables to describe the beach response, namely the crest height, the seaward (front) beach foot location, and the shoreward (rear) beach foot location. Three sand conservation equations govern the beach response.

A high-quality database on subaerial profile response due to wave impact and overwash in the field was compiled to validate the employed transport formulas and the analytical solutions to describe beach evolution. The field data included pre- and post-storm profiles and the associated wave and water level forcing, as well as sediment characteristics, for several major storm events. Also, a long-term time series of wave and water level data encompassing 70 years at a resolution of 1 hr was employed to calculate dune erosion and overwash transport for statistical analysis. These data originated from Ocean City (MD), and the long-term wave and water level data were used as input to the analytical

model to calculate time series of morphological impact parameters, primarily eroded volume, overwash volume, and recession distance. Empirical distribution functions were derived from these times series as a basis for assessing the probability of exceedance for a specific event.

II: SIGNIFICANT ADMINISTRATIVE ACTIONS AND OTHER INFORMATION

No significant administrative actions were taken.

III: FUNDS REMAINING AND LIST OF PROPERTY ACQUIRED

The total contract is for $570,000. Payment upon receipt of these reports is scheduled at $50,000. Therefore, the amount of funds remaining under contract at the end of this report period is $520,000.

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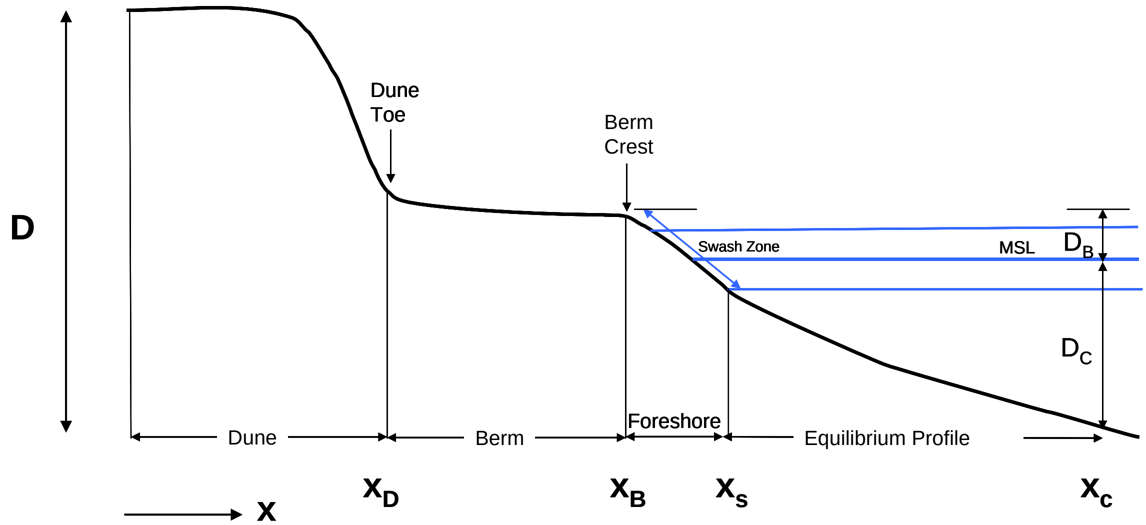

Figure 1. Definition sketch of dune and berm/foreshore complex.

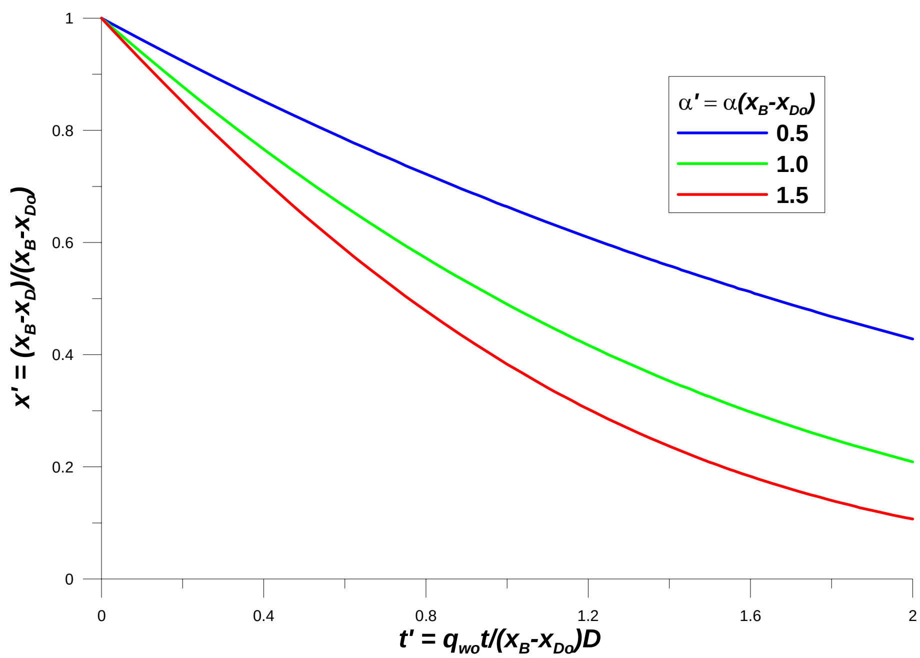

Figure 2. Non-dimensional evolution of the berm width for the case of fixed berm crest location and no dune erosion due to wave impact.

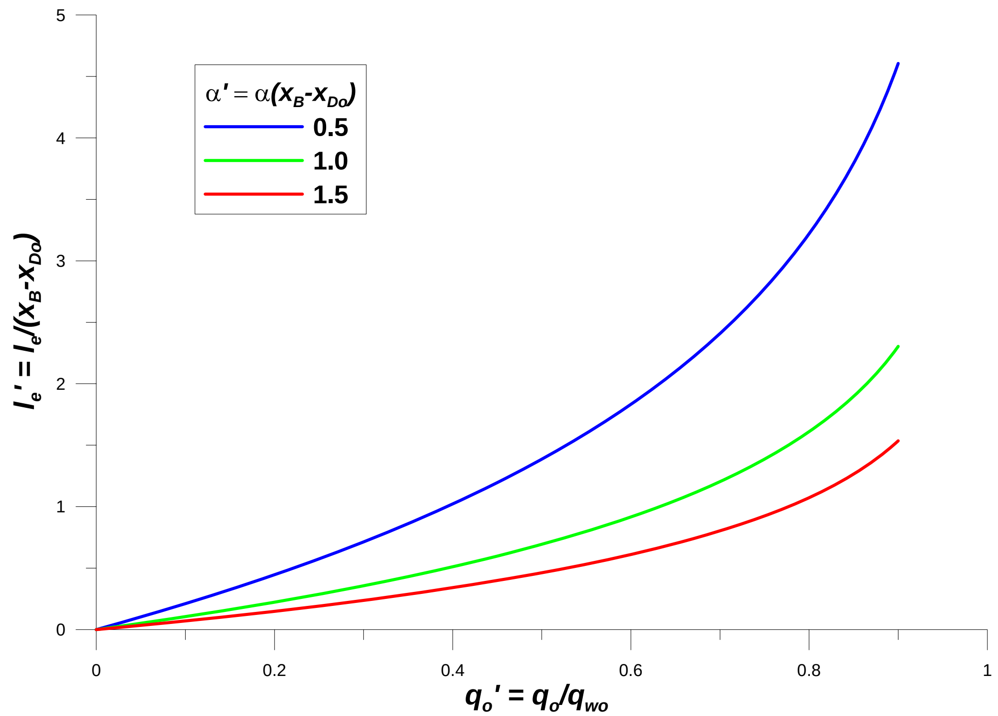

Figure 3. Non-dimensional equilibrium berm width as a function of the ratio between dune erosion due to wave impact and dune build-up by wind for different values on the non-dimensional rate coefficient.

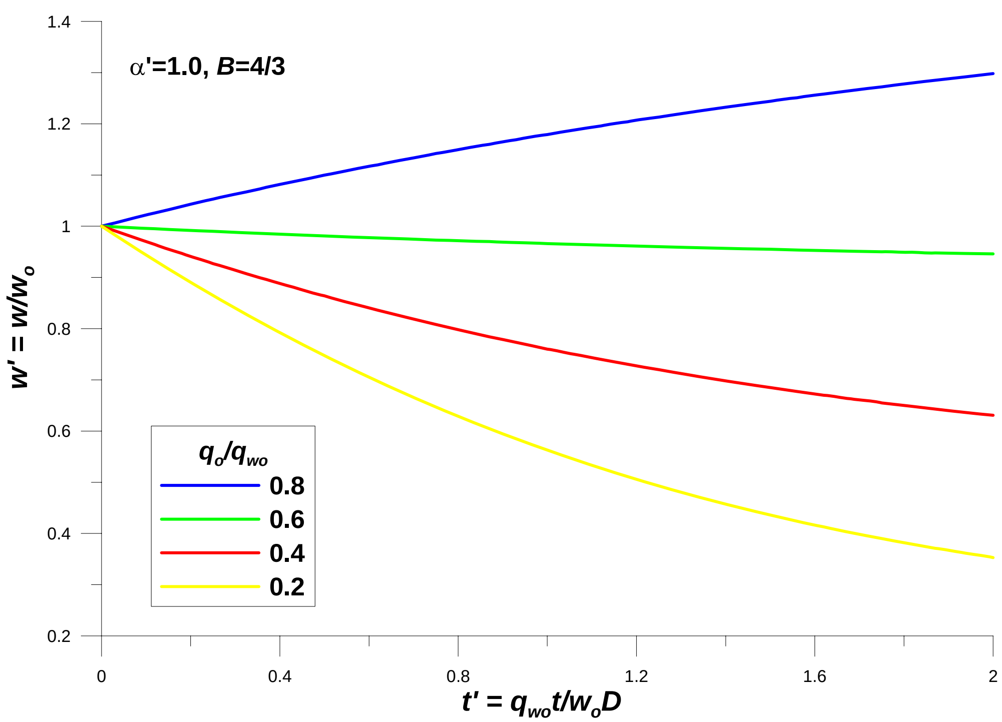

Figure 4. Non-dimensional evolution of the berm width for the case of moving berm crest location and dune erosion due to wave impact.

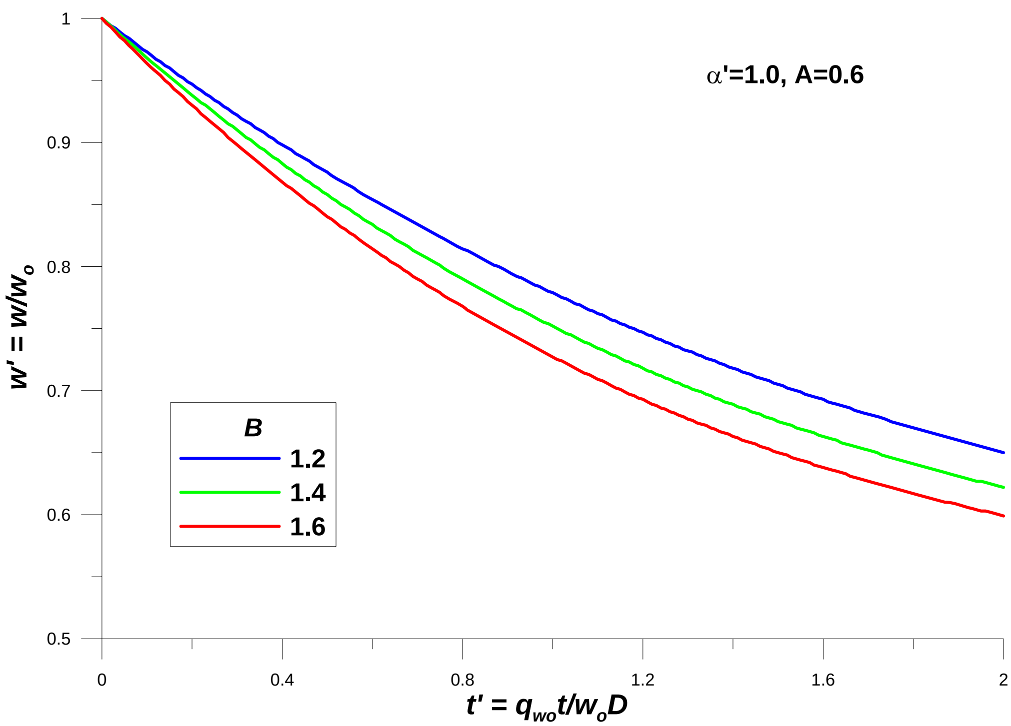

Figure 5. Non-dimensional evolution of the berm width for the case of moving berm crest location and dune erosion due to wave impact.

APPENDIX A:

Table of Contents for Technical Report on the Lund-CIRP Sediment Transport Model

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